ASTRONOMY

Early Solar System Chronology

Isotopic analysis of chondrules in primitive meteorites validates the use of ^{26}Al as a precise chronometer for early solar system events.

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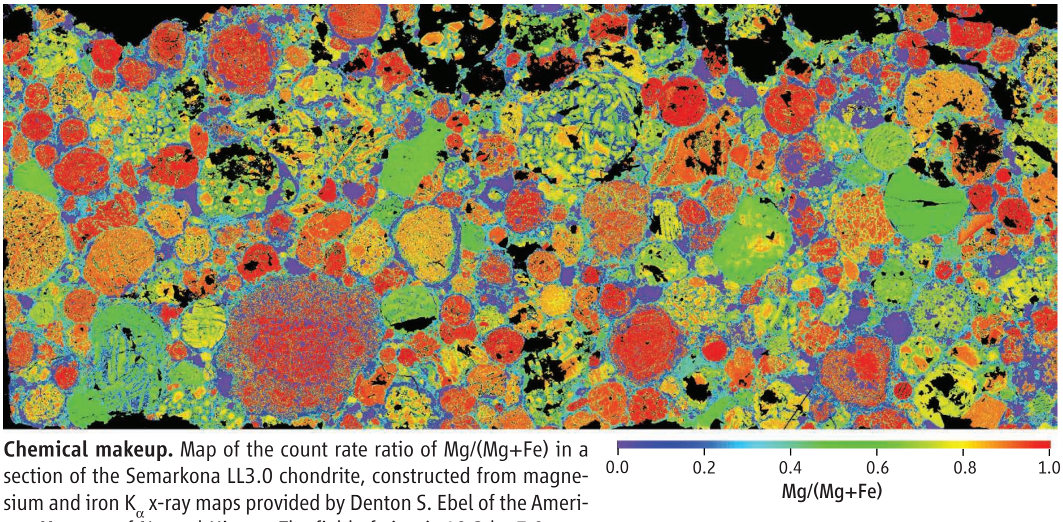
The short-lived radioisotope ^{26}Al (*1*) has long been used as a relative chronometer of events in the early solar system. However, although much is known about its initial abundance in the early solar system, there remain doubts on applicability of ^{26}Al chronometry, because it is not known whether it was uniformly distributed. On page 985 of this issue, Villeneuve *et al*. (*2*) report the development of new techniques that allow magnesium isotopic measurements to be made with unprecedented precision. They confirm that $^{26}Al/^{27}Al$ was indeed uniform in the early solar system to about the 10% level and find that chondrules formed in discrete events over a time period of more than 1 million years. These data are a major step forward in developing a precise and accurate chronometer, but also raise new questions about early solar system processes.



Chemical makeup. Map of the count rate ratio of Mg/(Mg+Fe) in a section of the Semarkona LL3.0 chondrite, constructed from magnesium and iron K_{α} x-ray maps provided by Denton S. Ebel of the American Museum of Natural History. The field of view is 19.2 by 7.8 mm. Type I chondrules are magnesium-rich and almost free of iron, and appear red. Type II chondrules are composed of magnesium and iron silicates and appear in green to orange colors. Fine-grained iron-rich matrix between chondrules is light blue in color, and metal and iron sulfides appear purple. Black denotes cracks and voids.

For ^{26}Al to be useful as a chronometer, the ratio of ^{26}Al to stable ^{27}Al must have been uniform in the solar system before the first solids formed. Because ^{26}Al decays to ^{26}Mg with a half-life of 0.73 million years, all of the early solar system ^{26}Al has decayed by now. The first issue to address is the fact that the source of ^{26}Al is not known. It may have come from a nearby supernova at the time of solar system formation, but it may also have been made in the solar system by particle irradiation from the young Sun (*3*). If ^{26}Al was injected into the solar system from an external source, it may not have been well mixed within the solar system. If ^{26}Al was made within the solar system, production could have continued for a long period of time, continually injecting fresh ^{26}Al.

Among the most interesting and puzzling discoveries related to the evolution of the solar system is that chondrules, which are the major constituent of the most common type of meteorite, chondrites, are about 2 million years younger than the oldest objects in the solar system—refractory calcium- and aluminum-rich inclusions (CAIs), which are also found in chondrites. It remains unclear whether this age difference between the formation of chondrules and CAIs, which is seen in both the ^{26}Al-^{26}Mg system and by Pb-Pb dating, the only long-lived chronometer with sufficient precision for early solar system events (*4*), is actually real.

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Villeneuve *et al*. have now used secondary ion mass spectrometry to measure magnesium isotopic compositions and Mg/Al ratios in the major phases (olivine, low-calcium pyroxene, and glass) in chondrules from the Semarkona LL3.0 chondrite. They then calculated the $^{26}Al/^{27}Al$ ratio at the time of crystallization of each chondrule from the slopes on isochron diagrams. Such measurements have been reported before, but the key feature in their study is the very precise determination of the magnesium isotopic composition that each chondrule had at the time of crystallization. By using high beam currents and paying meticulous attention to detector backgrounds, Villeneuve *et al*. have achieved precisions of 5 parts per million on measurements of the $^{26}Mg/^{24}Mg$ ratio in magnesium-rich minerals after correction for instrumental and natural mass-dependent fractionation.

Chondrules in primitive chondrites are of two major types, FeO-poor (type I) and FeO-rich (type II) (*5*). To use the ^{26}Al-^{26}Mg system as a chronometer, each chondrule must have been sufficiently heated during its formation to completely homogenize its magnesium isotopic composition. Libourel *et al*. have shown that glass is not in equilibrium with the minerals present in type I chondrules (*6*); therefore, Villeneuve *et al*. restricted themselves to type II chondrules. Plotting the initial magnesium isotopic composition at the time of each object's formation against the $^{26}Al/^{27}Al$ ratio, they show that Earth, the Semarkona chondrules, and the CAIs are on a single evolution line. The slope of this line is determined by the solar system Al/Mg ratio, an independently determined parameter, and favors the argument that $^{26}Al/^{27}Al$ was well mixed in the early solar system. This conclusion is consistent with recent evidence that ^{60}Fe, another short-lived isotope that was present early in solar system history, was also uniformly mixed to at least the 10% level (*7*).

That $^{26}Al/^{27}Al$ was uniform in the early solar system and usable as a chronometer will be reassuring to most in the field. Villeneuve *et al*. also found that the ^{26}Al-^{26}Mg ages of chondrules cluster, both in their data and earlier work, consistent with chondrules in ordinary chondrites forming in five discrete events spanning more than 1 million years. Ages of chondrules in carbonaceous chondrites also cluster, but occur at different times from those in ordinary chondrites. This clustering raises some important questions.

Chondrites are the most common type of meteorite but come in a number of types (ordinary chondrites, carbonaceous chon-

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drites, enstatite chondrites, and R chondrites). There are basically four different populations of chondrules, each associated with a particular type of chondrite (*5*). If the solar system was well mixed, as the ^{26}Al (*2*) and ^{60}Fe (*7*) evidence indicates, how is it that different types of chondrules ended up in different parent bodies when chondrule formation occurred over more than a million years? Data for both ordinary and carbonaceous chondrites indicate clustering in ^{26}Al-^{26}Mg ages, but in separate sets of events (*2*). It will be interesting to extend this record to enstatite and R chondrites. The high-precision techniques introduced by Villeneuve *et al*. should be extended to low Al/Mg phases in CAIs to further establish the solar system magnesium isotopic evolution curve.

References and Notes

1. T. Lee, D. A. Papanastassiou, G. J. Wasserburg, *Geophys. Res. Lett.* **3**, 109 (1976).
2. J. Villeneuve, M. Chaussidon, G. Libourel, *Science* **325**, 985 (2009).
3. F. H. Shu, H. Shang, T. Lee, *Science* **271**, 1545 (1996).
4. Y. Amelin, A. N. Krot, I. D. Hutcheon, A. A. Ulyanov, *Science* **297**, 1678 (2002).
5. E. R. D. Scott, A. N. Krot, in *Meteorites, Planets, and Comets*, A. M. Davis, Ed., Vol. 1, *Treatise on Geochemistry,* 2nd ed. (H. D. Holland, K. K. Turekian, Eds. (Elsevier, Oxford, 2007), pp. 1–72.
6. G. Libourel, A. N. Krot, L. Tissandier, *Earth Planet. Sci. Lett.* **251**, 232 (2006).
7. N. Dauphas *et al*., *Astrophys. J.* **686**, 560 (2008).
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ANTHROPOLOGY

Coastal Exploitation

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How did ancient hunter-gatherers influence coastal environments?

The development and spread of agriculture and pastoralism during the past 10,000 years is often seen as the tipping point when humans fundamentally changed our relationship with the natural world. Ancient hunter-gatherers also altered their environments, although the extent to which they did so remains hotly debated (*1*–*3*). Hunter-gatherers may have caused major alterations of terrestrial ecosystems, including the use of fire to enhance resource productivity and the translocation of various animals to new regions (*3*, *4*). They are implicated in massive megafaunal extinctions in the Americas and Australia (*2*, *3*). Recent archaeological research from coastal areas shows that they also substantially altered and enhanced marine ecosystems in other ways, some of which obscure the definition of the term "hunter-gatherer."

Shellfish, fish, and other coastal resources have been harvested by hunter-gatherers for more than 150,000 years, with the earliest evidence found in South Africa (*5*). Some early hunter-gatherers influenced the size and structure of near-shore shellfish populations by ~23,000 years ago—the earliest evidence for human impacts on marine populations to date (*6*, *7*). Shellfish size reductions intensified during the past 10,000 years as human populations grew and moved into new areas, but the declines documented by 23,000 years ago demonstrate human influence on the structure of near-shore organisms and ecosystems at a very early date—often millennia

Ancient fisheries. In this painting by Henry Wood Elliott from 1872, traditional Aleuts fish in kelp forests of the Aleutian Islands. For centuries or millennia, hunter-gatherers around the world used comparable technologies and techniques to exploit near-shore fisheries.

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before the earliest historical accounts.

Ancient exploitation of keystone species by hunter-gatherers also affected the structure and function of near-shore coastal ecosystems. Native American predation of sea otters in California after ~9000 years ago and in the Aleutians ~3000 years ago allowed abalone and sea urchin populations to expand greatly, changing the entire structure of the kelp forest ecosystem. Such "trophic cascades" may have resulted in localized urchin barrens (areas where sea urchin populations are so large that entire kelp forests are depleted) (*8*, *9*). Compared with those seen in contemporary or historical kelp forests, these ancient urchin barrens may have been short-lived or localized, however, with human harvest of urchins replacing the predatory controls once provided by sea otters.

Cod, a keystone species that is depleted in the North Atlantic today, may have been locally overfished by hunter-gatherers in the Gulf of Maine beginning some 3500 years ago, with archaeological data indicating the greatest reduction in larger, older individuals (*10*). This may have reduced predation pressures on lower trophic level animals, especially medium-sized predators such as floun-

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